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FATIGUE DAMAGE SENSING USING ACOUSTIC EMISSION

JOSEPH R. POKORSKI, P.E.
BURTON R. FISHER

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STRUCTURES TEST BRANCH
STRUCTURES DIVISION
FLIGHT DYNAMICS DIRECTORATE
WRIGHT LABORATORY
WRIGHT-PATTERSON AFB, OHIO
45433-6553

FOREWORD

This work was performed by the Instrumentation Group, Structures Test Branch, Structures Division, Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson Air Force Base, Ohio, and Physical Acoustics Corporation, Princeton, New Jersey. The study reported in this technical memorandum was conducted in suppport of In-house Laboratory Independent Research (ILIR 0007) Nr. 88-12, "Fatigue Damage Sensing Using Acoustic Emission".

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This document has been reviewed and is approved.

GEORGE R. HOLDERBY
Chief, Stuctures Test Branch
Structures Division

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I - INTRODUCTION

Acoustic Emission (AE) is the transient elastic wave energy created when there is a rapid release of energy in a material. Three ways this may happen are: 1. Plastic deformation; 2. Phase transformation; 3. Material fracture and crack growth.

In structural fatigue testing, ~~AE~~ Acoustic Emission can be used to sense the beginning of fatigue damage (crack initiation) and then to monitor growth. If the initiation of damage can be detected early and then located on the structure, then downtime may be avoided or at least reduced to a minimum as the defect can be continuously monitored or repaired. Other methods for locating structural damage usually involve periodic shutdown of the test while visual inspections and other Non-Destructive Inspection (NDI) techniques are carried out. In addition to lost valuable time this often involves a partial teardown of the structure. AE monitoring, on the other hand, involves passive monitoring of the test article while it is being cycled in load during fatigue testing.

The AE system acquired by the Structures Test Branch Instrumentation Group (FIBTA) at Wright Laboratory is a 32-channel system manufactured by Physical Acoustics Corp. (PAC). The system was assembled from off-the-shelf components available from PAC, but was acquired through a government contract with the Grumman Corp. in which the task was to evaluate various NDI methods and then determine which technique would be most promising for use during fatigue tests to monitor for the onset of damage. Beyond that, the contractor was to assemble an automated system which could be operated by technician level personnel and to prove its capabilities by demonstrating its use on a fatigue test. A similar system has been in use for several years at McClellan AFB on F-111 cold proof tests. With the system being completely computer controlled, the user defines all AE test parameters from a single "SETUP" file which initializes the hardware settings. Computer interfacing also allows real-time source detection and location which may be presented to the user in various tabular and graphical forms.

The Instrumentation Group of the Structures Test Branch (WL/FIBT) used the automated fatigue damage sensing system using acoustic emission (AE) to locate the sources of possible structural failure during the fatigue test on the F-15 aircraft in the Structures Test Facility. The prototype automated early fatigue damage sensing system was developed under Air Force Contract F33615-83-C-3225 by Grumman Aerospace Corporation and Physical Acoustics Corporation.

The objective was to detect initiation and growth of fatigue cracks during structural fatigue tests. The present fatigue damage sensing system, expanded to 32 channels of acoustic emission sensors, monitored the critical areas of the F-15 fatigue test aircraft. The center fuselage section was studied and sensors were installed on Bulkheads 558.5, 595.9, and 626.9. The upper surface of the left wing was studied and sensors were installed on the skins covering the spars and ribs in the torque box area, which experiences the highest loads. A total of 18 sensors were used in the center fuselage area (6 sensors per bulkhead) and 14 sensors were used to monitor the wings. The attenuation levels in these areas of the F-15 were established by these studies. These attenuation studies are documented in Physical Acoustics Corporation Report "F-15 Acoustic Emission Attenuation Studies", 3 May 1988.

SECTION II - F-15 ACOUSTIC EMISSION ATTENUATION STUDIES

During the period of 14 through 17 December 1987, Physical Acoustics Corporation (PAC) personnel visited the Flight Dynamics Directorate, Wright Laboratory at Wright-Patterson Air Force Base. The purpose was to investigate the ability of acoustic emission to monitor a F-15 full-scale fatigue test at the Structures Test Branch. Physical Acoustics Corporation decided to follow procedures established during its successful implementation of acoustic emission monitoring on F-111 aircraft undergoing cold-proof testing at McClellan Air Force Base.

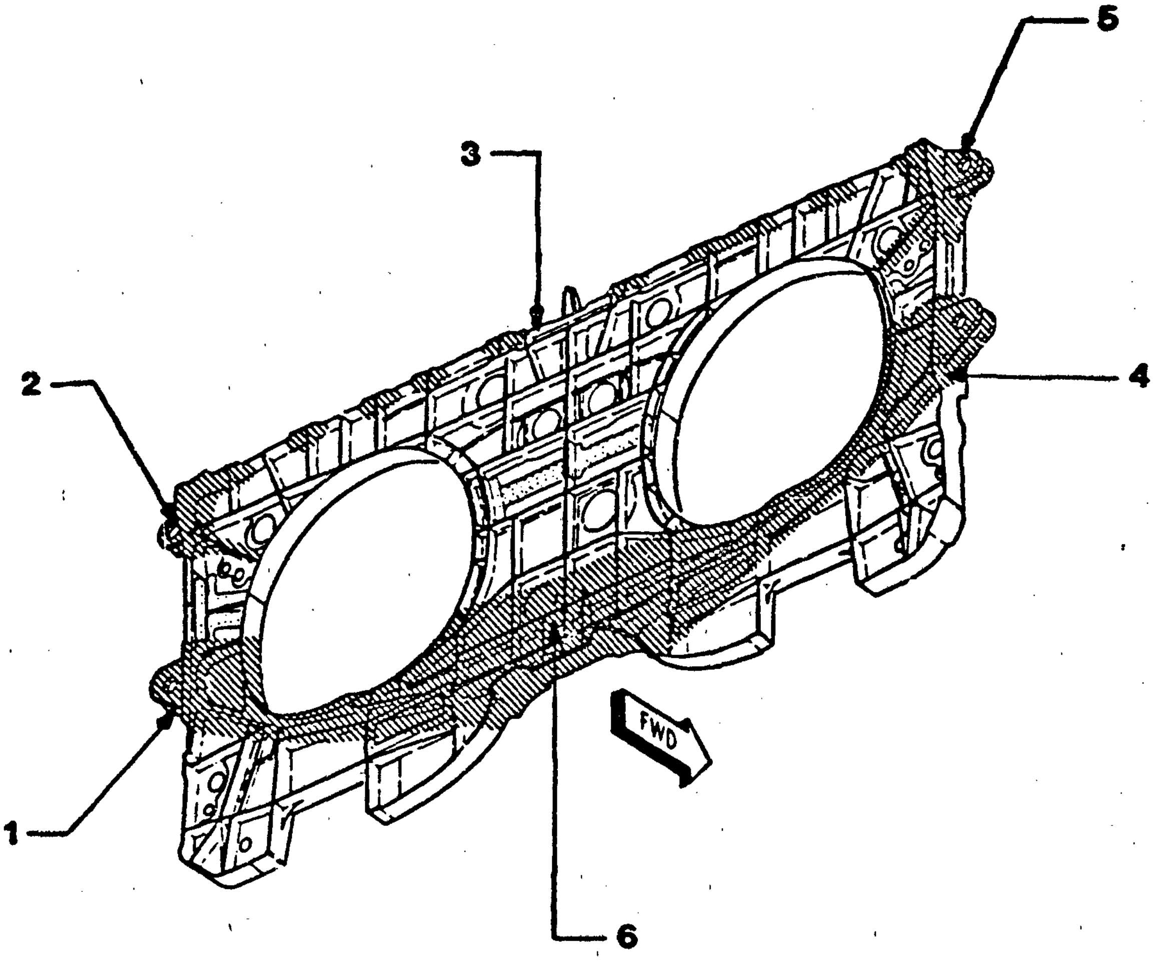
The approach called for consulting with aircraft structural personnel to define the critical areas requiring monitoring, experimenting with various sensor placements to adequately cover the critical areas, establishing system operating settings in order to reject innocuous structural noises and accept cracking signals, and finally to embody the information into a computer file to permit acoustic emission testing to be performed in a semi-automatic manner. During this visit it was only possible to define the critical areas of the F-15 and to experiment with sensor placements.

Two broad areas on the aircraft were investigated. These were the fuselage center section and the port wing upper surface. They were selected because they would exhibit the highest stresses during fatigue testing and because they were relatively accessible for sensor attachment. The acoustic emission equipment chosen for the effort was a PAC 3000/SPARTAN-12 system that had been delivered as the result of the Air Force contract with Grumman Aerospace Corporation.

The center fuselage section was the first area to be studied. Work started by instrumenting the 558.5 bulkhead with six micro-30 sensors (resonant frequency of 300 kHz). Data was collected from the 558.5 bulkhead, then the sensors were removed and placed on the 595.9 bulkhead. Data was then collected from the 595.9 bulkhead, following which the sensors were removed, placed on the 626.9 bulkhead, and data collected from it. The locations of the sensors are shown in Figure 1 for the 558.5 bulkhead, Figure 2 for the 595.9 bulkhead, and Figure 3 for the 626.9 bulkhead.

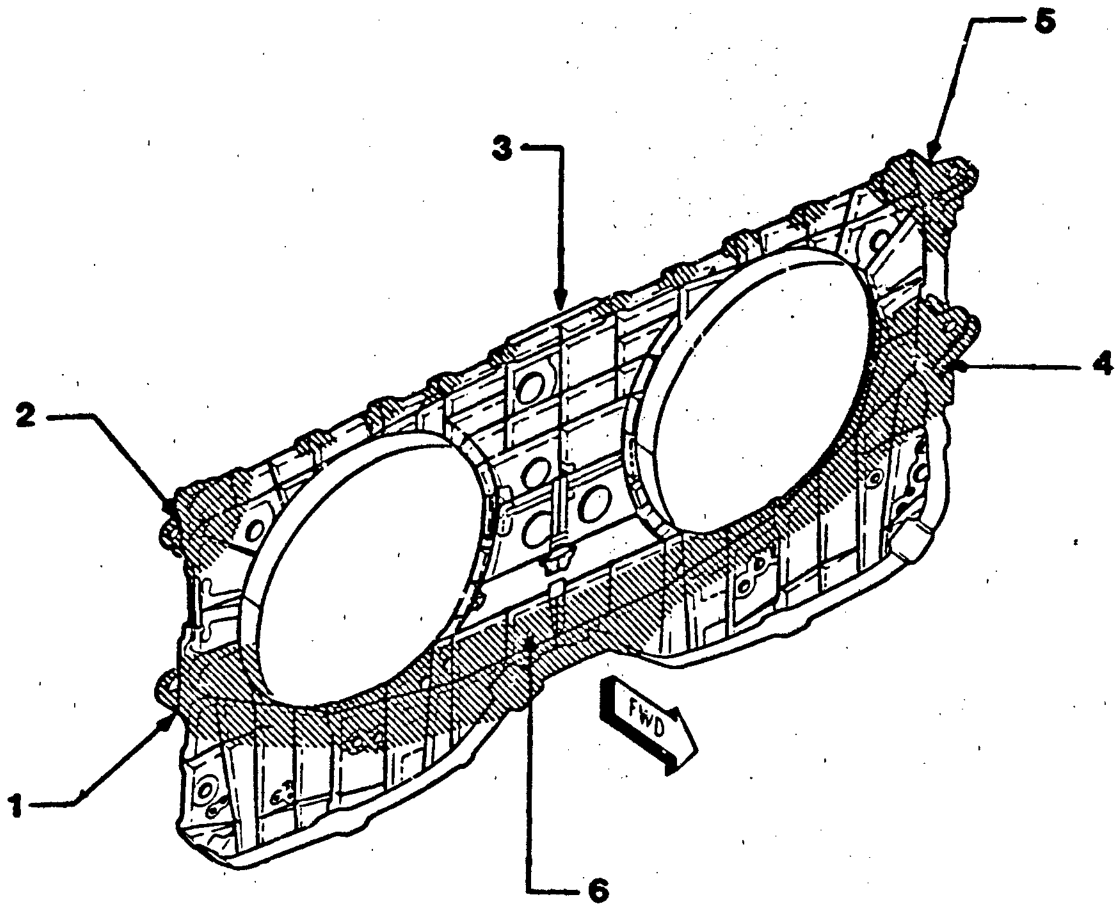
The sensors were attached temporarily to each bulkhead using yellow hot glue - clear hot glue was tried, but it was found to be impossible to acoustically couple the sound into the sensors with the clear hot glue. PAC does not recommend the use of hot glue for sensor attachment which must last for more than 8 hours, as the joint degrades acoustically after that time. In this case the sensors were only required to be attached for less than 2 hours, so the selection of hot glue was appropriate. For long term monitoring, an epoxy resin is recommended.

Simulated acoustic emission was generated in the bulkheads by breaking the lead of a Pentel 0.5 mm mechanical pencil. This is an industry standard simulated source, documented in ASTM 976, "Guide for Determining the Reproducibility of Acoustic Emission Sensor Response". The acoustic coupling between a sensor and a bulkhead was checked for acceptability by observing the amplitude of lead breaks next to each sensor; amplitudes in excess of 95 dB indicated good coupling. Then more pencil leads were broken at various locations on each bulkhead. The simulated acoustic emission was picked up by the 6 sensors installed on the specific bulkhead under investigation, and the results recorded by the SPARTAN system. From this information the acoustic attenuation between sensors on each bulkhead was deduced. The attenuation



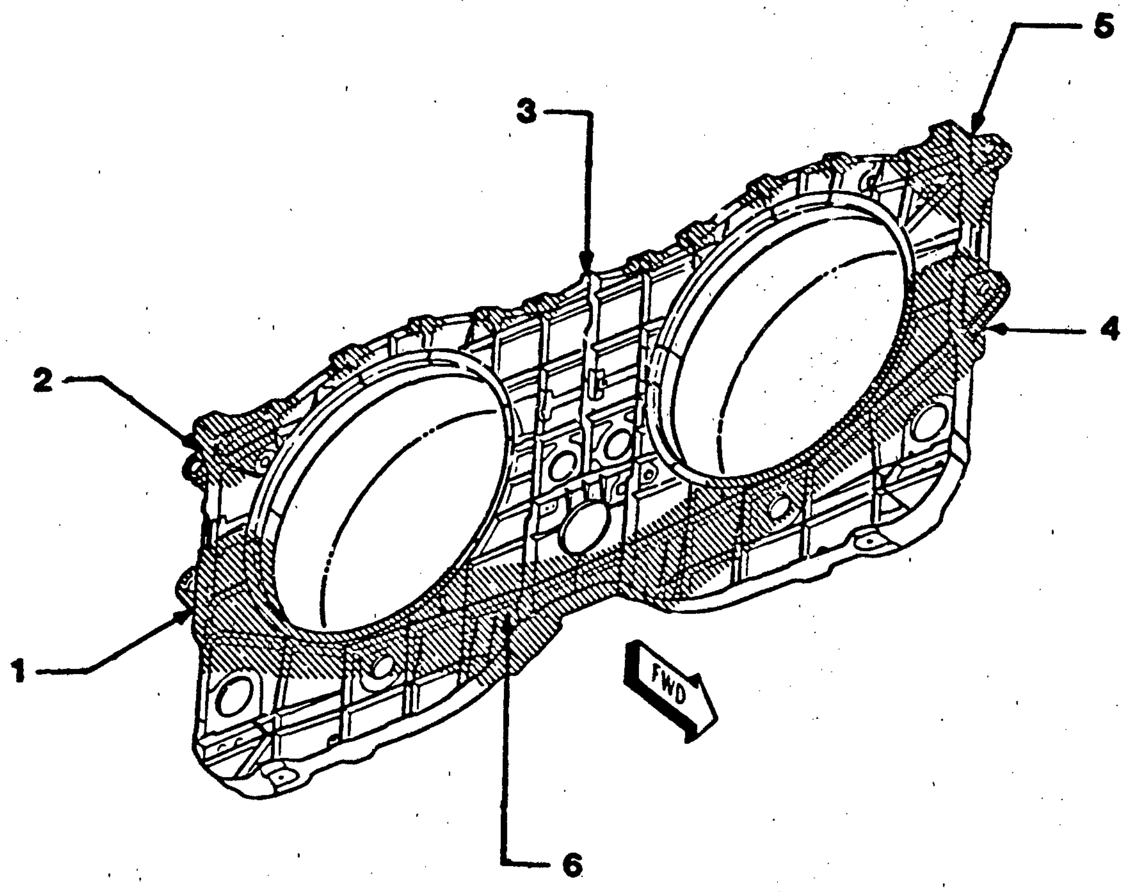
Sensor Pair	Attenuation	Sensor Pair	Attenuation
1-2	35 dB	1-6	>66 dB
2-3	55 dB	1-3	>66 dB
3-5	55 dB	3-4	60 dB
5-4	33 dB	3-6	>66 dB
4-6	50 dB		

Figure 1. Sensor locations on the 558.5 bulkhead, and attenuation between sensors



Sensor Pair	Attenuation	Sensor Pair	Attenuation
1-2	35 dB	1-6	55 dB
2-3	61 dB	1-3	>66 dB
3-5	60 dB	3-4	58 dB
5-4	35 dB	3-6	>66 dB
4-6	62 dB		

Figure 2. Sensor locations on the 595.9 bulkhead, and attenuation between sensors



Sensor Pair	Attenuation	Sensor Pair	Attenuation
1-2	40 dB	1-6	50 dB
2-3	60 dB	1-3	>66 dB
3-5	50 dB	3-4	60 dB
5-4	40 dB	3-6	>66 dB
4-6	>66 dB		

Figure 3. Sensor locations on the 626.9 bulkhead, and attenuation between sensors

results for the bulkheads are shown along with the sensor locations in Figures 1, 2 and 3.

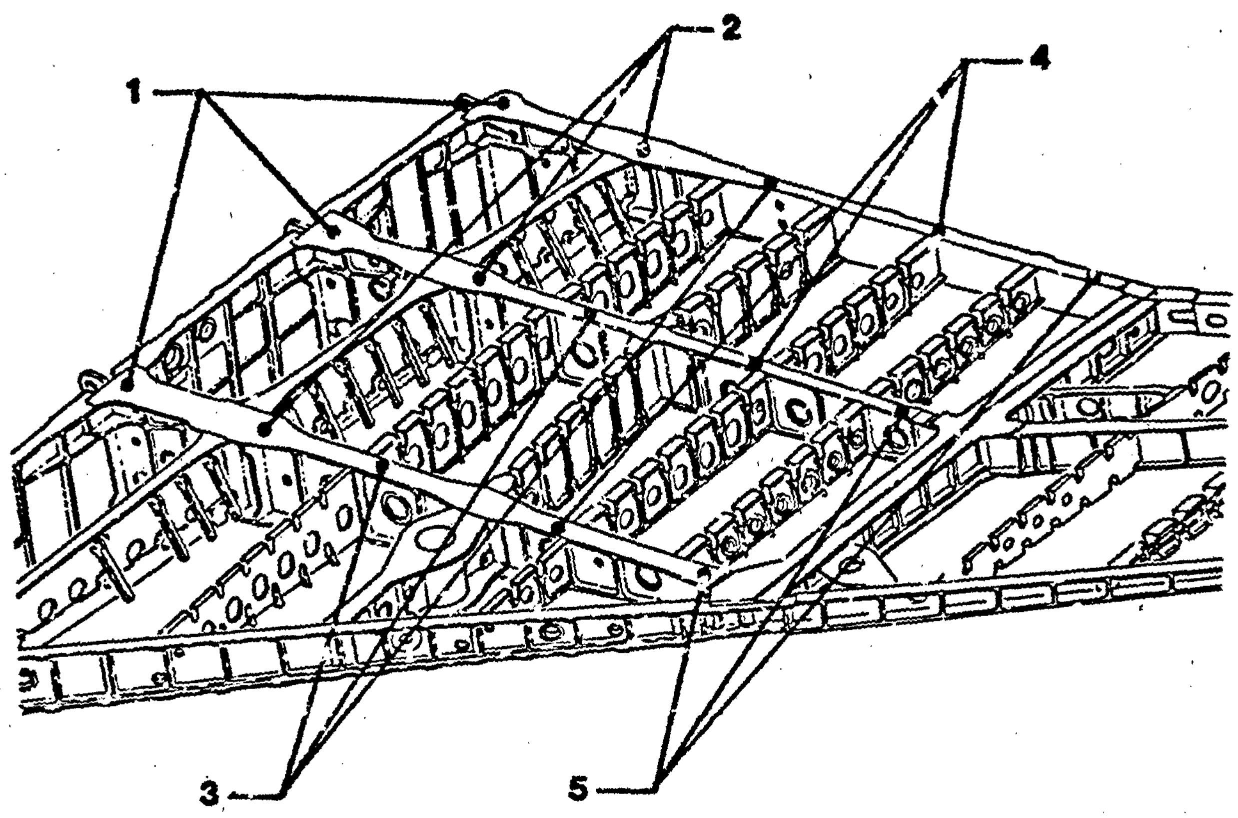
The investigation then moved to the upper surface of the port wing. Due to the large number of 4 inch by 4 inch pads which were attached to the wing for the application of the simulated flight loading, it was not possible to investigate all of the spars and ribs in the torque box area which would experience the highest loads. Instead, five sensors were attached, in turn, to the upper surface of the wing along spar YW 153.151, spar YW 190.151, spar YW 221.551, rib XW 77.4, rib XW 99.0, and rib XW 128.877. The exact locations of the sensors are shown on Figure 4 for the spars, and Figure 5 for the ribs. As was done on the bulkheads, yellow hot glue was used to provide a temporary acoustic coupling. Lead breaks were then performed to check the acceptability of the acoustic coupling. Finally, pencil leads were broken at various locations on the wing, with the results recorded by the SPARTAN system. From this information, the acoustic attenuation between sensors was deduced. The attenuation results for the port wing spars and ribs are shown along with the sensor locations in Figures 4 and 5.

In order to appreciate the meaning of the results, it was necessary to place them in the context of the contemplated acoustic emission testing on the F-15. First, the SPARTAN has a dynamic range of 85 dB, i.e., if the maximum signal is 100 dB the minimum that can be recorded is 15 dB. Second, the whiffle-tree loading used on the F-15 was inherently noisy and well coupled to the airframe. This means that extraneous noise would be recorded along with acoustic emission from structural failure processes. To get rid of the extraneous noise, rejection filters were used that depend on signal characteristics such as energy, rise time and duration. This did not get rid of all of the noise, though, and to limit signal processing it was necessary to raise the acceptance threshold from the minimum of 15 dB. In practice, this generally requires a threshold of 40 dB. Thus the dynamic range of the SPARTAN is usually artificially limited to 60 dB because of noise considerations. The net result of all of this is that sensors should be placed no more than 60 dB apart so that it is insured that multiple sensors will detect the presence of a single acoustic emission source. In this fashion, source location can be accomplished.

The sensor to sensor attenuation results obtained on the F-15 center fuselage and port wing are shown in Figures 1, 2, 3, 4, and 5. It can be seen that the sensor placements for the bulkheads met the objective of being less than 60 dB apart, except for propagation paths from the port lower wing attachment lug to the upper mid-line of the bulkhead, and from the upper mid-line to the lower mid-line of the bulkhead. Because of the magnitudes of the attenuation values obtained for the bulkheads, it was recommended that they be monitored using 6 sensors per bulkhead. Use of any fewer sensors would result in incomplete coverage on the bulkheads.

The sensor positions used on the port wing provided too complete a coverage. Here it was possible to use fewer sensors. As a suggestion, the placing of 3 sensors per spar was adequate since the attenuation between positions 1 and 3 and positions 3 and 5 on the spars gave values on the order of 60 dB. It should be noted that positioning the sensors on the spars did not preclude the monitoring of the ribs, as the attenuation value along the ribs between spars was on the order of 60 dB, also.

The reasons for the discrepancy between the size of the monitored area and the number of sensors needed was interesting. Because the bulkheads were single pieces of metal, their attenuation factor was due to pure geometrical



Forward Spar

Sensor Pair	Attenuation	Sensor Pair	Attenuation
1-2	47 dB	4-5	51 dB
2-3	38 dB	1-3	60 dB
3-4	54 dB	3-5	60 dB

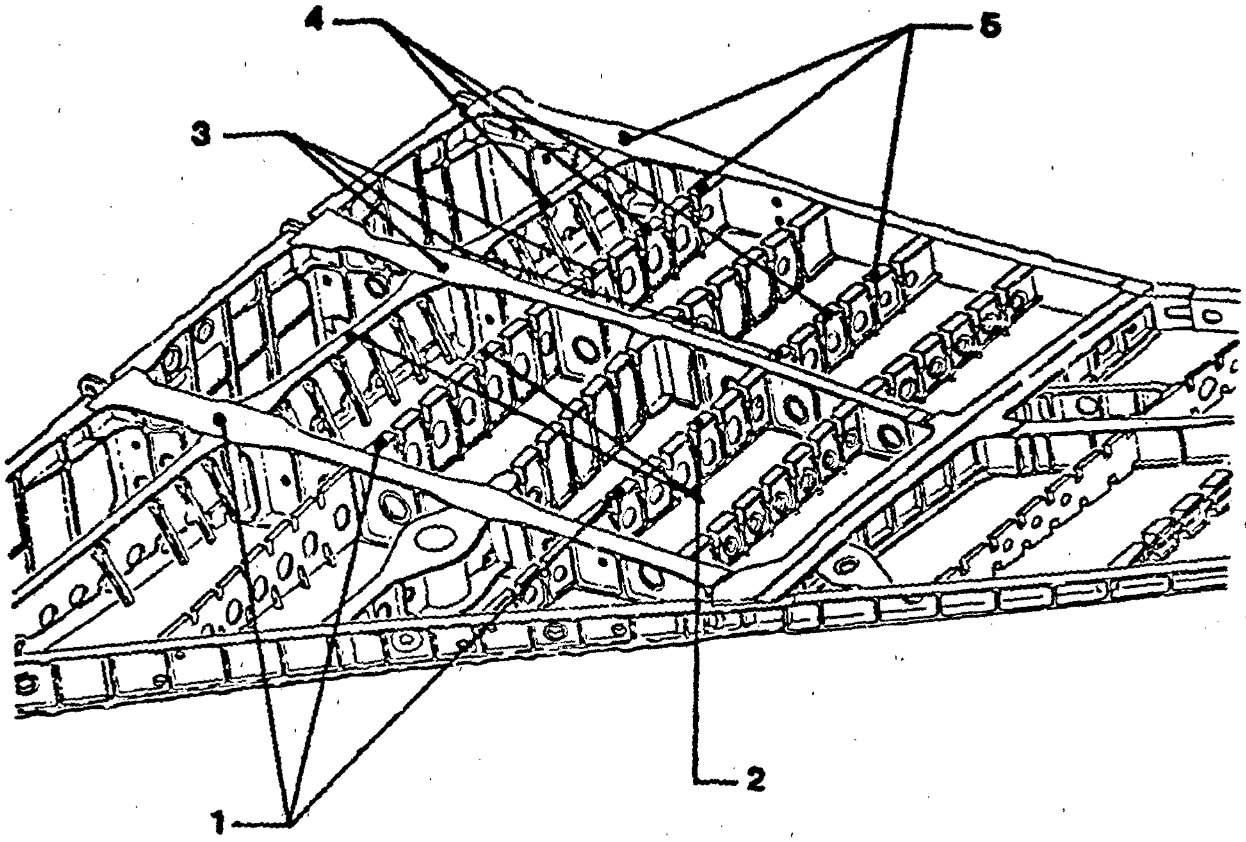
Middle Spar

Sensor Pair	Attenuation	Sensor Pair	Attenuation
1-2	45 dB	4-5	52 dB
2-3	36 dB	1-3	59 dB
3-4	52 db	3-5	62 dB

Aft Spar

Sensor Pair	Attenuation	Sensor Pair	Attenuation
1-2	48 dB	4-5	44 dB
2-3	37 dB	1-3	58 dB
3-4	56 dB	3-5	51 dB

Figure 4. Sensor locations on the port wing spars, and attenuation between sensors



Inboard Rib

Sensor Pair	Attenuation	Sensor Pair	Attenuation
1-2	48 dB	4-5	46 dB
2-3	48 dB	1-3	>66 dB
3-4	44 dB	3-5	61 dB

Middle Rib

Sensor Pair	Attenuation	Sensor Pair	Attenuation
1-2	41 dB	4-5	25 dB
2-3	[illegible] dB	1-3	61 dB
3-4	38 dB	3-5	36 dB

Outboard Rib

Sensor Pair	Attenuation	Sensor Pair	Attenuation
1-2	41 dB	4-5	35 dB
2-3	39 dB	1-3	60 dB
3-4	35 dB	3-5	43 dB

Figure 5. Sensor locations on the port wing ribs, and attenuation between sensors

spreading and losses caused by absorption due to stress fields in the metal. The wing, however, was constructed of numerous pieces of sheet metal and fasteners, with sealant applied between the contacting surfaces of the metal pieces. The attenuation factor for the wing was therefore due not only to geometrical spreading and stress field absorption losses, but was also due to acoustic impedance changes caused by bolted joints and poor contact between the constituent elements of the wing. Thus the number of sensors needed for the bulkheads was dictated mainly by size and geometry, while the number of sensors needed for the wing was dictated mainly by acoustic attenuation complexity.

The attenuation in the structure of the F-15 was fairly high, meaning that it required a large number of sensors to adequately detect acoustic emission arising from cracking. Specifically, it required at least 6 sensors per bulkhead to achieve sensor to sensor attenuation of less than 60 dB. This was a total of 18 sensors for the center fuselage area. Each wing required at least 9 sensors to monitor the spars only, for a grand total of 36 sensors.

The feasibility of using acoustic emission, as far as signal propagation is concerned, for monitoring the fatigue testing of a F-15 was established. However, more work needed to be done in order to apply it properly. Specifically, the establishment of proper system operating settings in order to reject innocuous structural noises and accept cracking signals had to be accomplished, as did the embodiment of all acoustic emission test specific information into the computer file to permit acoustic emission monitoring to be performed in a semi-automatic manner.

SECTION III - ACOUSTIC EMISSION SYSTEM

Physical Acoustics Corporation recommended that the PAC 3000/ SPARTAN-12 system, bought by the Air Force under contract F33615-83-C-3225 to Grumman Aerospace Corporation, should be expanded to include at least 36 channels in order to more completely collect acoustic emission from the F-15 fatigue test. Due to funds limitation, the present fatigue damage sensing system was expanded to 32 channels of acoustic emission sensors to monitor the critical areas of the F-15 fatigue test aircraft. Six sensors were installed on each of the Bulkheads 558.5, 595.9, and 626.9 as shown in Figures 1, 2, and 3. Six sensors were installed on the upper surface of each of the wings as shown in Figure 6.

The purpose of this acoustic emission system was to locate sources of structural failure on the F-15 fatigue test aircraft during fatigue cycling. Structures Test Branch engineers, in cooperation with Physical Acoustics Corporation consultants, established proper system operating settings in order to reject innocuous structural noises and accept fatigue cracking signals.

The major problem in application of AE to test monitoring is the fact that any cause and/or source of elastic wave energy will be detected if parameters are not specifically tailored to one type of signal only. This is an extremely difficult problem in structures of large scale and complexity where extraneous sources of noise are many and are often higher in amplitude and occur more frequently. Attempts to discriminate against meaningless signals is done in several ways, the first of which is frequency filtering. Frequency filtering begins with the sensor itself; the piezoelectric crystal is designed with a specific inherent resonant frequency. Matching this frequency with that most often occurring in wave energy release from cracks will be a first step in focusing in on real data. Further filtering is also accomplished using band-pass filters upon first amplifying the microvolt level signals.

By defining certain parameters in the "SETUP" file, the incoming signal may be compared to these pre-established characteristics and then accepted or rejected based on the comparison. The user defined parameters are described as follows:

1. Threshold Amplitude - the minimum amplitude before a signal is considered meaningful as the bulk of signals below this level are due to extraneous noise; signals that never rise above this level are rejected.

2. Peak Definition Time - the time which begins at first signal apex and runs for a user defined length of time (Peak Definition Time); if a new peak is hit before time runs out, the clock is reset and begins again; when the clock has completely run out, rise time and peak amplitude are established.

3. Hit Definition Time - time which begins when a signal has first dropped back below the threshold and runs for a user defined length of time (Hit Definition Time); if the signal rises back above the threshold before time runs out, the clock is reset to zero and begins again when the signal drops below the threshold; when the clock has completely run out, the signal duration is defined.

4. Hit Lockout Time - time which begins when the signal has ended and locks the system out of the data gathering mode for a user defined length of time (Hit Definition Time) so that wave reflections are not interpreted as being new data.

SENSOR LOCATIONS

WING STRUCTURES

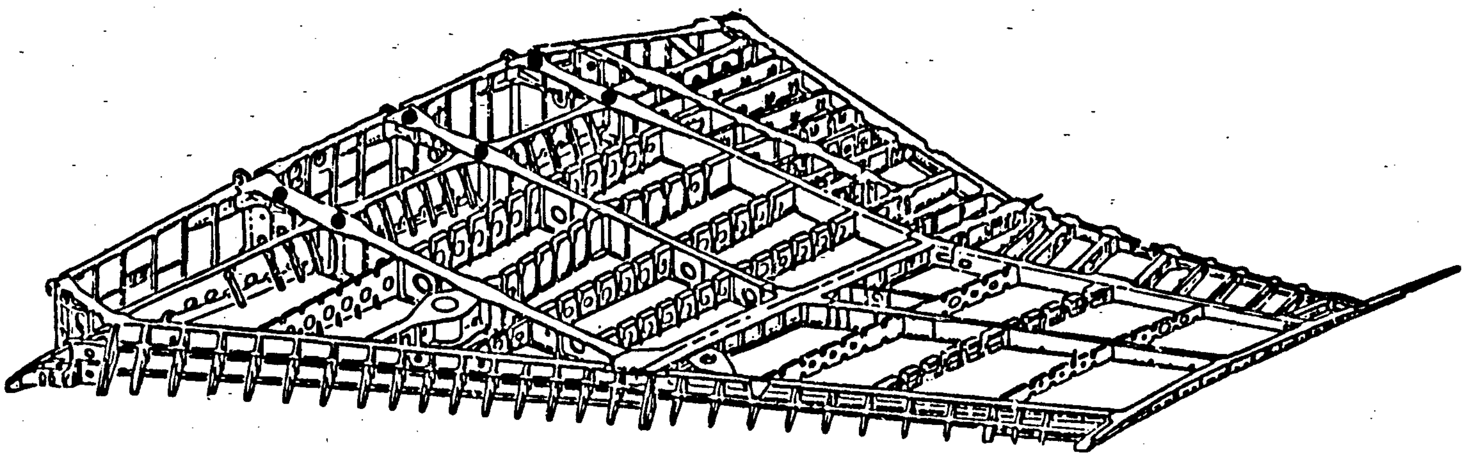


Figure 6
Location of Acoustic Emission
Sensors- F-15 wing

After a signal has been detected according to the above parameters, it can be described to the user in terms of its duration, peak amplitude, rise time to peak amplitude, counts (number of times it has crossed the threshold level), and energy (area under the amplitude versus time curve). During post test analysis, data can be further reduced by correlating data graphically or by other means. For example, plotting duration or energy versus amplitude, continuous mechanical noise would be seen as high energy but low amplitude. Electromagnetic interference on the other hand would be high in amplitude. but low in energy or duration. The Fatigue Damage Sensing System description, setup, operation, and software description are detailed in the Technical Report AFWAL-TR-88-3008, May 1988 (Reference 2).

SECTION IV - ACOUSTIC EMISSION TESTING

Physical Acoustics Corporation served as a consultant during the initial acoustic emission instrumentation of the F-15 to advise on precise sensor placement, sensor attachment method, system operating settings needed to reject innocuous structural noises and accept cracking signals, and general system usage.

The purpose of this accustic emission system was to locate sources of structural failure on the F-15 fatigue test. WL/FIBT established proper system operating settings in order to reject innocuous structural noises and accept fatigue cracking signals. The embodiment of all acoustic emission test specific information into the computer file permitted acoustic emission monitoring to be performed in a semi-automatic manner. The test data were recorded, monitored, and evaluated during fatigue cycling. Physical Acoustics Corporation also served as a consultant on an as needed basis during the F-15 fatigue testing program to assist in the interpretation of the data. Maps of flaw detection suspected areas on the F-15 fatigue test aircraft were prepared. The evaluations of these areas were coordinated with the periodic inspection of the test article.

The acoustic emission system was used in the laboratory by Professor M. Hamstad, University of Denver, under a 1990 summer faculty research program sponsored by the Air Force Office of Scientific Research (Reference 9). Professor Hamstad plotted the parasitic noise inherent in the system. He also investigated different methods of crack location in homogeneous materials. Specifically, he investigated the use of the AE source location algorithm in FIBT's 32-channel SPARTAN AE system and improved source location algorithms using transient recorder data. He showed that the SPARTAN system does not have the accuracy required to locate crack tips with sufficient accuracy for smart structures applications. The lack of accuracy is due to the way the SPARTAN system determines the arrival time of the stress waves at the sensors. Using the transient recorder data, he identified the source of the errors in the SPARTAN arrival time data and investigated means for improving the determination of the arrival times at the sensors. He showed that the source location algorithm can be improved considerably by using stress waveform information.

SECTION V - RESULTS

Physical Acoustics Corporation performed an analysis of acoustic emission data recorded during fatigue cycling of the F-15 fatigue test aircraft. The main areas of interest were the bulkheads. Figure 7 shows the results of the flaw detection system on Bulkhead 558.5. Figure 8 shows the results of the flaw detection system on Bulkhead 595.9. Figure 9 shows the results of the flaw detection system on Bulkhead 626.9. Figure 10 shows the results of the flaw detection system on the overall plan view of the F-15 fatigue test aircraft. All of these areas detected were coordinated with the NDE inspection evaluations of the F-15 fatigue test aircraft.

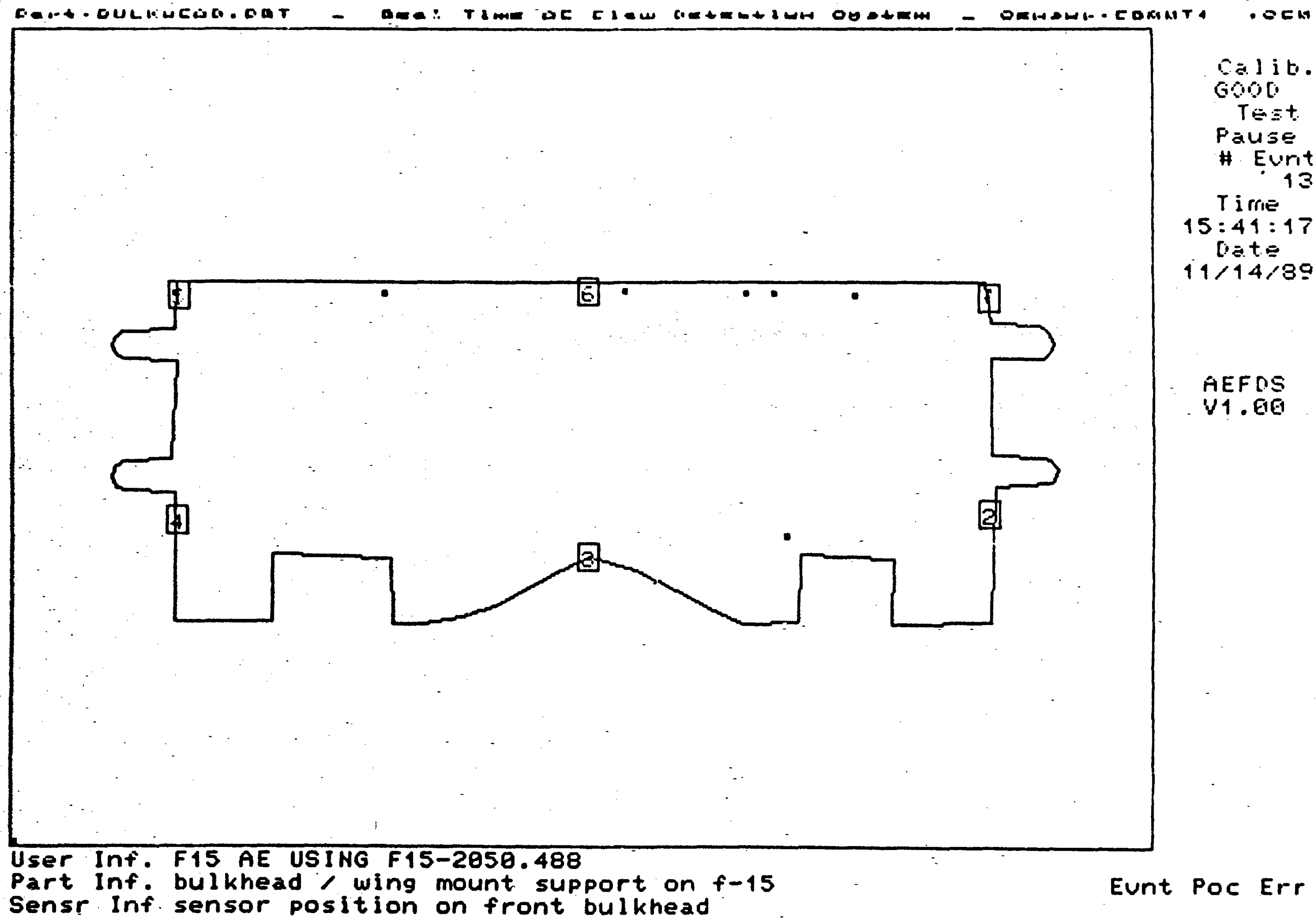


Figure 7. Flaw Detection on F-15 Bulkhead 558.5

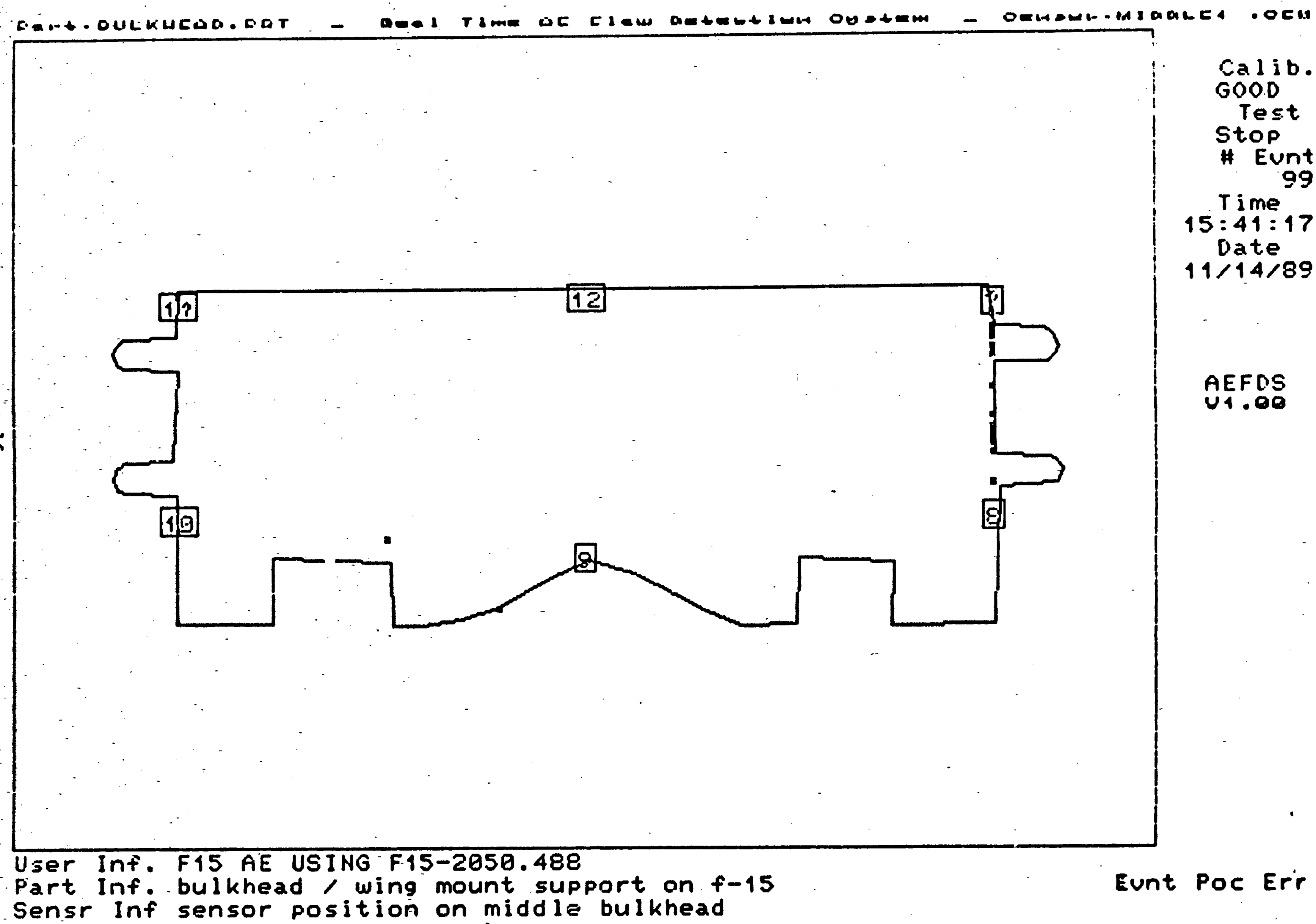


Figure 8. Flaw Detection on F-15 Bulkhead 595.9

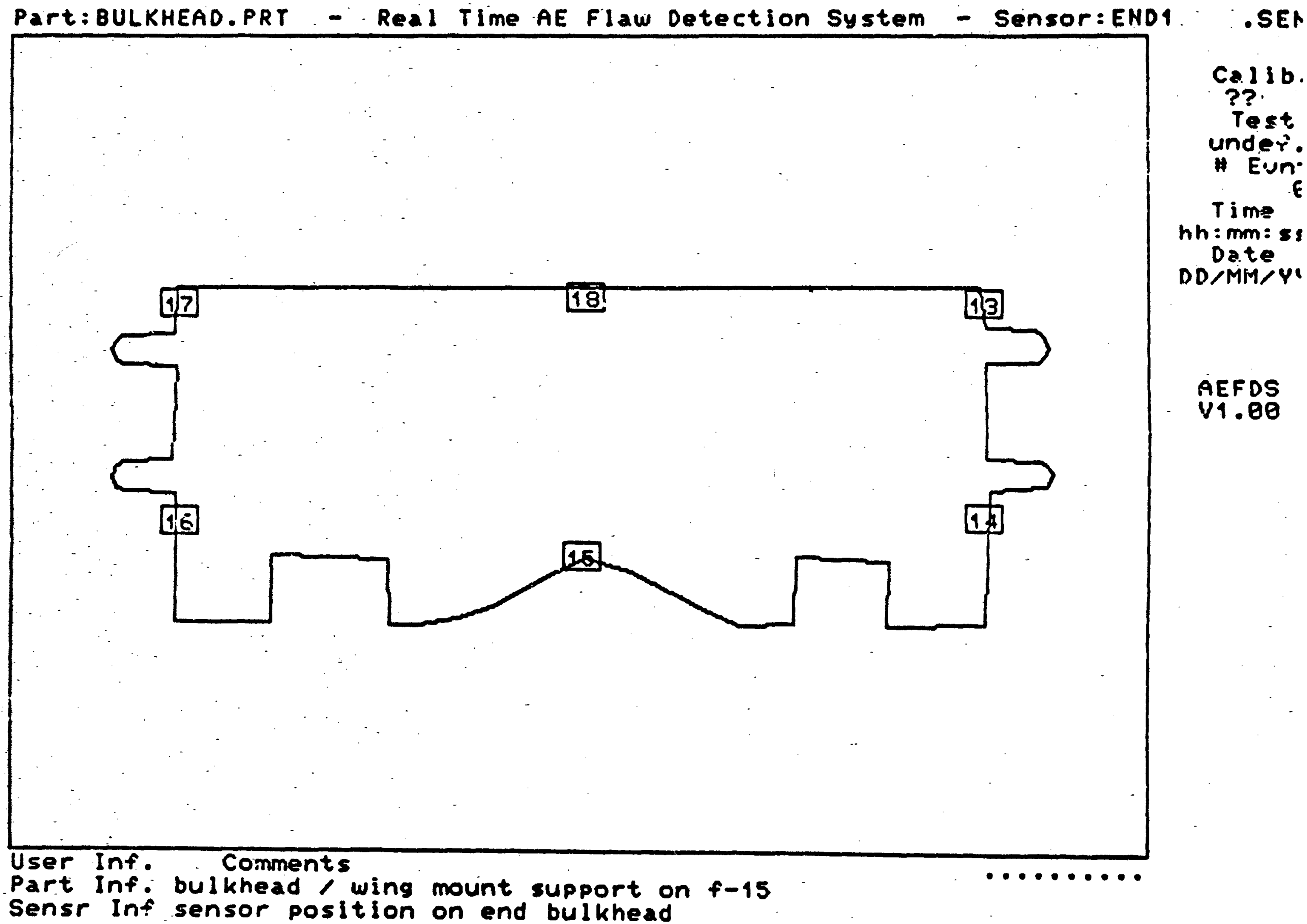


Figure 9. Flaw Detection on F-15 Bulkhead 626.9

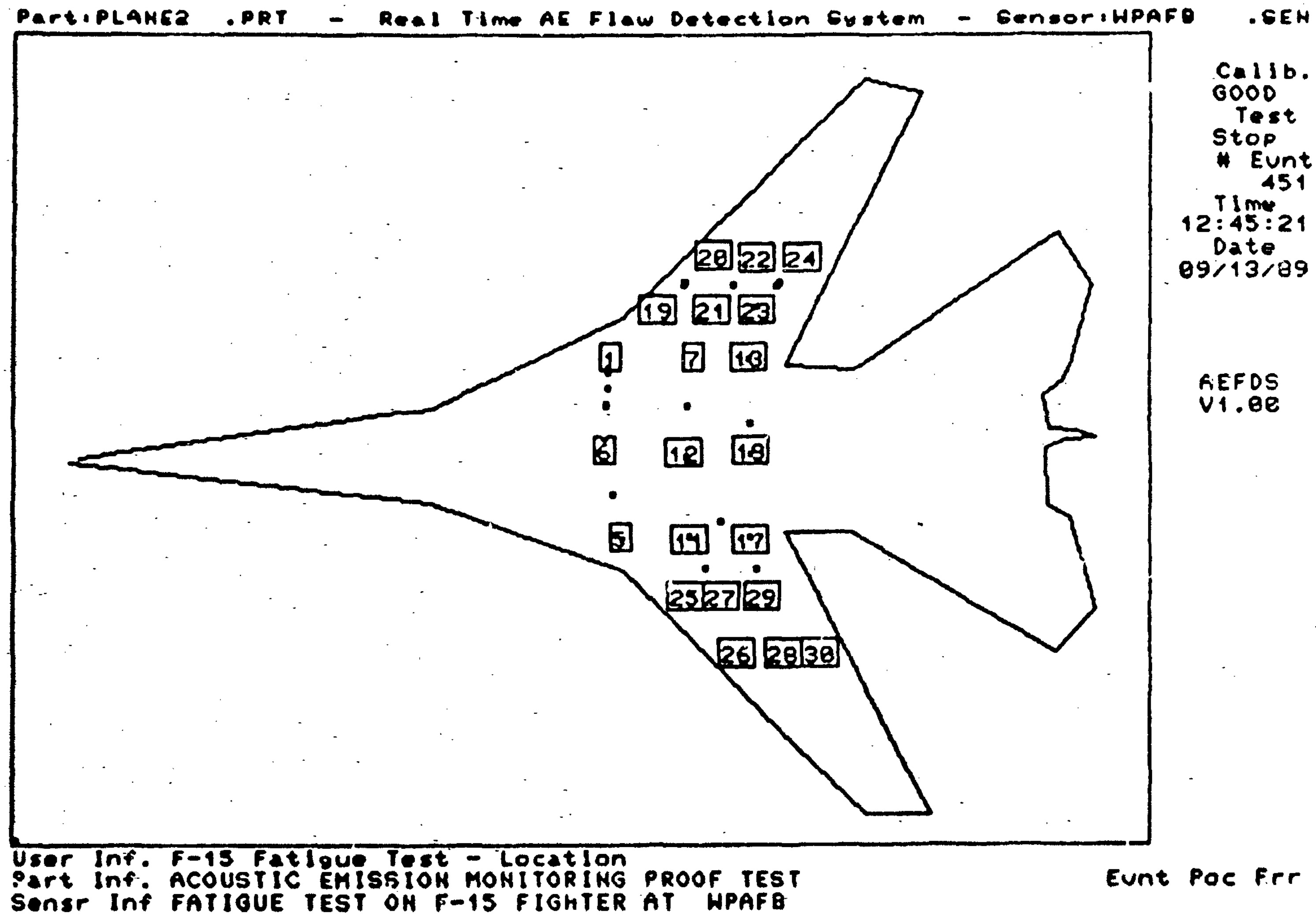


Figure 10. Flaw Detection on Plan View of F-15

SECTION VI - CONCLUSIONS

The major problem in the application of AE to test monitoring is the fact that any cause and/or source of elastic wave energy will be detected if parameters are not specifically tailored to one type of signal only. This is an extremely difficult problem in structures of large scale and complexity where extraneous sources of noise are many and are often higher in amplitude and occur more frequently.

An evaluation of the effectiveness of the acoustic emission system on the F-15 full-scale fatigue test was inconclusive to determine the successful development of the use of AE to detect fatigue cracks on aircraft structures. The acoustic emission technology is still in the R&D laboratory stage.

The successful use of acoustic emission for the detection of fatigue cracks in structures requires trained, knowledgeable, and experienced personnel for understanding how wave propagation influences the acoustic emission signals and for analyzing the test data.

The research performed showed that the measurement of the acoustic emission signal arrival times using a fixed threshold may lead to errors. The underlying causes are the complex specimen geometry, the nonsymmetrical radiation intensity patterns from the acoustic emission source, and the sensitivity differences between acoustic emission channels. [Hamstad, 1990].

Acoustic emission technology is constantly improving with new and better sensor/preamplifier combinations and with improved measurement techniques. The basic acoustic emission waveform data can provide essential data to locate fatigue cracks, but improved sensor sensitivity is needed. Advanced technology may overcome many of the difficulties encountered.

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